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NLTE abundances of Cr in the Sun and metal-poor stars

Maria Bergemann[*†]
Max-Planck-Institut für Astrophysik
E-mail: mbergema@mpa-garching.mpg.de

We investigate statistical equilibrium of Cr in the atmospheres of late-type stars. The main goal is to ascertain the reason for a systematic abundance discrepancy between Cr I and Cr II lines, which is often encountered in spectroscopic analyses of metal-poor stars. Up to now, all these studies relied on the assumption of local thermodynamic equilibrium (LTE) in the spectrum modelling. For the first time, we perform NLTE calculations in subdwarfs and subgiants of different metallicities. We show that the LTE assumption is inadequate to describe excitation-ionization equilibrium of Cr I/Cr II in stellar atmospheres and, as a result, leads to large errors in abundances. In particular, the NLTE abundance corrections to Cr I lines range from $+0.3$ to $+0.5$ dex at low [Fe/H]. The NLTE [Cr/Fe] trend in the halo and the disk is flat and can be reproduced by most of the models of Galactic chemical evolution with standard prescriptions for Cr and Fe nucleosynthesis.

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[*]Speaker.

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1. Introduction

There is a well-known problem with modelling excitation and ionization balance of Cr in the atmospheres of late-type stars. Systematic differences of $0.1 - 0.5$ dex between abundances based on LTE fitting of the Cr I and Cr II lines were reported for metal-poor giants and dwarfs (e.g. Johnson 2002, Lai et al. 2008, Bonifacio et al. 2009). The discrepancies are smaller in the atmospheres with larger metal content, amounting to ~ 0.1 dex for Galactic disk stars (Prochaska et al. 2000) and for the Sun (Sobeck et al. 2007, Asplund et al. 2009). It is common to attribute these offsets to the *overionization* of neutral Cr, a typical NLTE phenomenon affecting minority atoms in stellar atmospheres. However, this explanation lacks theoretical justification, because calculations of statistical equilibrium of Cr in model atmospheres under restriction of different stellar parameters have not been performed up to now.

This discrepancy has important implications for Galactic chemical evolution studies, which rely on gradients of observed abundance ratios. Depending on the ionization stage of Cr used for abundance calculations in metal-poor stars, radically different trends of [Cr/Fe] with [Fe/H] are obtained. The constant [Cr/Fe] with metallicity, as derived from LTE analyses of Cr II lines, has a simple interpretation in the theory of nucleosynthesis. Cr is co-produced with Fe in explosive Si-burning that occurs in SNe, and the production ratio Cr/Fe is roughly solar in both SNe II and SNe Ia. On the other side, there is no simple explanation for declining [Cr/Fe] ratios with decreasing [Fe/H], which follows from LTE analyses of Cr I lines. Recent studies of metal-free massive stars and their nucleosynthesis yields show that *subsolar* Cr/Fe abundance ratios in very metal-poor stars can not be reproduced by any combination of SN II model parameters (e.g. Heger & Woosley 2008), especially when other Fe-peak elements are taken into account.

Here, we report NLTE abundances of Cr for the Sun and a sample of dwarfs and subgiants with $-3.2 \leq$ [Fe/H] ≤ -0.5. The description of the methods is given in Sect. 2. The statistical equilibrium of Cr under restriction of different stellar parameters is discussed in Sect. 3. The NLTE abundances for the observed stellar sample are presented in Sect. 4.

2. Methods

Restricted NLTE calculations for Cr were performed with the code DETAIL and the model of Cr atom was constructed with the data from the Kurucz database[1]. In short, the model includes 339 levels of Cr I/II and the number of radiatively-allowed transitions is 6806. The quantum-mechanical photoionization cross-sections for quintet and septet states of Cr I were taken from Nahar (2009). For all other levels, the Kramer's formula was adopted. For the rates of electronic and inter-atomic collisions, we used standard prescriptions. In particular, we investigated the sensitivity of results to the poorly-known rates of transitions due to collisions with H I, which are usually approximated by the formulae of Drawin (1969). The details about NLTE calculations, as well as parameters of the lines selected for the abundance analysis, can be found in Bergemann & Cescutti (2010). The abundances of Cr were computed by a method of spectrum synthesis with the code SIU (T. Gehren, private communication). All calculations were performed with 1D plane-parallel models MAFAGS-ODF (Grupp 2004) with Kurucz's opacity distribution functions. Stellar parameters,

[1] http://kurucz.harvard.edu/

$T_{\rm eff}$, $\log g$, and [Fe/H], were taken from Gehren et al. (2004, 2006), who used the same model atmospheres.

3. Statistical equilibrium of Cr

Similar to other complex minority atoms in the atmospheres of late-type stars, such as Fe I, the overall distribution of atomic level populations in Cr I is determined by the interplay of several processes. Overionization and photon pumping are due to the non-local UV radiation field with mean intensity larger than the local Planck function $J_\nu > B_\nu(T_{\rm e})$. These are counteracted by photon suction and overrecombination due to $J_\nu < B_\nu(T_{\rm e})$ at infra-red frequencies. Deviations from LTE caused by non-thermal radiation field are balanced by collisional coupling between levels. The relative role of these processes is different for stellar atmospheres with different $T_{\rm eff}$, $\log g$, and [Fe/H].

In general, deviations from LTE in Cr I develop in the atmospheric layers where the mean intensity exceeds the Planck function over the bound-free edges of well-populated Cr I levels with excitation energies $\sim 2-4$ eV. Overionization is particularly strong from the levels with large quantum-mechanical photoionization cross-sections. For the Sun, the role of transitions in strong near-UV lines is non-negligible. They influence the Cr I excitation balance in the outer layers of the solar model atmosphere, $\log \tau_{500} < -2$. In the deeper regions, where many weak observable Cr I lines are formed, the collisional interaction of the Cr I levels with each other is quite strong. So that NLTE abundance corrections are relatively small, ≤ 0.1 dex for the majority of lines.

In the atmospheres of cool metal-poor dwarfs and subgiants, radiative processes dominate over collisions. NLTE effects on the levels of Cr I and Cr II are amplified compared to the solar case and grow with decreasing [Fe/H]. As a result of low metal abundances, the effect of line-blanketing is reduced leading to increased UV fluxes and collisional coupling between the levels is very weak due to deficient electrons. Deviations from LTE in Cr I are sensitive to effective temperature and gravity at low metallicity. In the cool models, the effect of gravity is very pronounced. For example, at [Fe/H] $= -3$, departures from LTE for Cr I levels are stronger in the model with $T_{\rm eff} = 5000$ K and $\log g = 2.6$ than in the model with $T_{\rm eff} = 6000$ K and $\log g = 4.2$, despite larger $T_{\rm eff}$ of the latter model. This may account for a systematic difference between metal-poor giants and dwarfs found by Lai et al. (2008) and Bonifacio et al. (2009).

4. Abundances of Cr for the Sun and metal-poor stars

The solar abundance was determined by comparing synthetic Cr lines with the Solar Flux Atlas of Kurucz et al. (1984). Oscillator strengths for the majority of Cr I transitions were taken from Sobeck et al. (2007), who estimate the accuracy of $\log gf$'s to be better than $\sim 10\%$.

The solar LTE abundance of Cr determined from the Cr I lines is 5.66 dex with $\sigma = 0.04$ dex. This value is consistent with the meteoritic abundance, 5.63 ± 0.01 dex[2]. The LTE abundance based on the Cr II lines is 5.81 ± 0.13 dex that makes a large abundance discrepancy between the Cr I and Cr II lines, ~ 0.15 dex. In contrast to LTE, the difference between both ionization stages

[2]The Cr abundance in CI-chondrites from Lodders et al. 2009 was renormalized to the photospheric Si abundance of Shi et al. (2008), $\log \varepsilon_{\rm Si,\odot} = 7.52$ dex

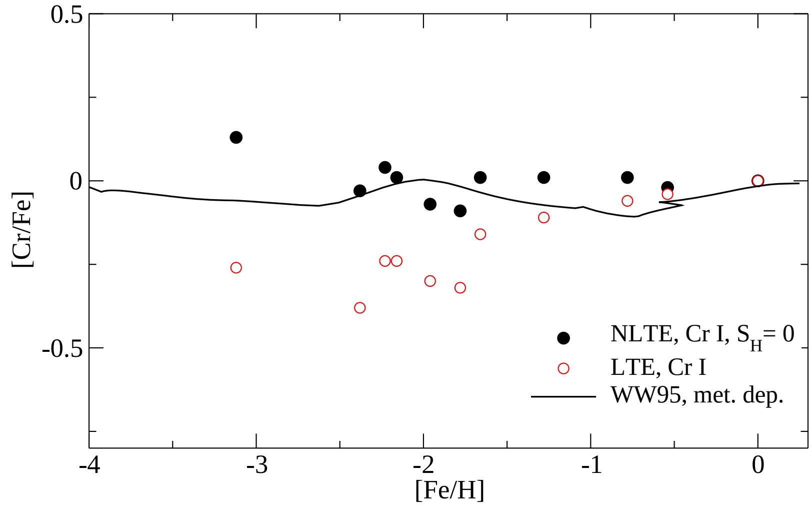

Figure 1: Abundance ratios [Cr/Fe] as a function of metallicity. NLTE and LTE-based Cr abundances in metal-poor stars are marked with filled and open symbols. The evolutionary curve for [Cr/Fe] (black trace) was computed with the chemical evolution model for the solar neighborhood. See text.

in NLTE is fairly small. Neglecting inelastic collision with H I in the calculations of Cr population densities, $S_{\mathrm{H}} = 0$, we derive $\log \varepsilon = 5.74 \pm 0.05$ from the solar Cr I lines and $\log \varepsilon = 5.79 \pm 0.12$ dex from the Cr II lines. The results for $S_{\mathrm{H}} = 0.05$ are not very different from the previous case, $\log \varepsilon = 5.7 \pm 0.04$ dex (Cr I) and $\log \varepsilon = 5.79 \pm 0.12$ dex (Cr II). A few Cr I and Cr II lines give systematically higher abundances. Since these lines are sensitive to microturbulence parameter, this anomaly most likely reflects the shortcomings of our 1D model atmospheres.

A very low efficiency of inelastic H I collisions is also favored by the ionization equlibrium of Cr I/Cr II in the metal-poor stars. We have analyzed 10 stars[3] from different Galactic populations with spectra obtained by T. Gehren and collaborators with UVES spectrograph at the VLT (Paranal) and/or with the FOCES spectrograph at the 2.2m telescope of the CAHA observatory (Calar Alto). The NLTE Cr I -based abundances in metal-poor stars are systematically larger than those computed under LTE approach (Fig. 1). The difference of $0.2-0.4$ dex is due to substantial overionization of Cr I at low metallicity. The LTE abundances determined in this work using Cr I lines are consistent with other LTE studies, confirming that declining [Cr/Fe] with metallicity is an artifact of the LTE assumption in line formation calculations. The mean NLTE [Cr/Fe] ratio in stars with subsolar metallicity computed from Cr I lines assuming $S_{\mathrm{H}} = 0$ is $\langle[\mathrm{Cr/Fe}]\rangle = 0$ with the standard deviation $\sigma = 0.06$ dex. Using the Cr II lines, we derive $\langle[\mathrm{Cr/Fe}]\rangle = -0.05 \pm 0.04$ dex. The finding that [Cr/Fe] remains constant down to lowest metallicities is consistent with nucleosynthesis theory, which predicts that Cr and Fe are co-produced in explosive Si-burning in supernovae in roughly solar proportions.

The NLTE [Cr/Fe] trend with [Fe/H] is reproduced by most of the Galactic chemical evolution models, without the need to invoke peculiar conditions in the ISM or to adjust theoretical stellar

[3]The details on observational material and derivation of stellar parameters can be found in Bergemann & Cescutti (2010).

yields. The theoretical evolution of [Cr/Fe] in the solar neighborhood (see Bergemann & Cescutti 2010 for details), computed with the two-infall GCE model of Chiappini et al. (1997) is in agreement with the NLTE results (Fig. 1). The model predicts that $\sim 60\%$ of the total solar Cr and Fe are due to SNe Ia and the rest due to SNe II, the latter synthesize both elements in roughly solar proportions. The underproduction of Cr relative to Fe in SNe Ia is compensated by its overproduction in solar-metallicity SNe II.

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